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Payback times and multiple midpoint/endpoint impact categories about Building-Integrated Solar Thermal (BIST) collectors

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ABSTRACT

The purpose of the present article is the evaluation, by means of life cycle assessment, of a system which consists of vacuum-tube solar thermal collectors. The system is appropriate for building integration and it has been developed in France. The methods ReCiPe and USEtox have been adopted. Regarding life-cycle results, according to the scenario «without recycling» and for 30-year system lifespan, ReCiPe payback time was calculated to be 18.14 years based on France´s electricity mix whereas by using Spain´s electricity mix (hypothetical scenario) it was found to be 4.03 years. Recycling offers a ReCiPe-payback time reduction of 2.66 years based on France´s electricity mix and 0.59 years based on Spain´s electricity mix. All the studied cases show ReCiPe payback times much lower than an assumed system-lifespan of 30 years. On the basis of ReCiPe midpoint and by considering material manufacturing of the 16 collectors and the additional elements of the system (scenario «without recycling»), among glass-, aluminium-, copper- and steel-based components, the copper-based ones present the highest impact in 15 of the 18 impact categories. For instance, for Freshwater eutrophication, the copper-based elements have a score that is around 30 times higher comparing to that of the aluminium-based ones. The USEtox findings, for the material manufacturing of the 16 collectors and the supplementary elements of the system and for the scenario «without recycling», reveal that the material with the highest total score in terms of: i) human toxicity/cancer is copper (6.7E-09

CTU_h), ii) human toxicity non-cancer is propylene glycol (4.0E-08 CTU_h), iii) ecotoxicity is copper (2.06 CTU_e). Recycling of the metals, according to USEtox, offers an impact reduction of 20-95%. A discussion about factors that influence the environmental profile of building-integrated solar systems is also provided.

Keywords: Building-Integrated Solar Thermal (BIST) system; Vacuum-tube solar thermal collectors; Life Cycle Assessment (LCA); ReCiPe, USEtox; Human health, Ecosystems, Resources; Ecotoxicity, Human toxicity

[1]

1. INTRODUCTION

Towards urban sustainability and environmentally sustainable cities, solar energy systems offer multiple eco-friendly solutions but there are some environmental issues such as recycling and inputs during the use stage that should be taken into account (Lamnatou et al., 2015a, 2016). Regarding the integration of solar systems in buildings, there are two main categories: 1) Building-Added (BA) configurations: The systems are added to the building, after construction is completed, and they do not serve as part of the building structure, 2) Building-Integrated (BI) configurations: The systems are part of the building structure. BI solar systems are energy-producing structures and they: i) have double functionality because they produce energy and, at the same time, they serve as a building element (glazing, façade, etc.), ii) provide environmental benefits. An additional advantage is the fact that BI solar systems are incorporated into the building in an aesthetically pleasing way. In the literature, solar thermal systems that are BI are known as Building-Integrated Solar Thermal (BIST) systems (Lamnatou et al., 2015a, 2016). Moreover, BI solar systems offer

[1] **ABBREVIATIONS:** BA: Building-added; BI: Building-integrated; BIST: Building-integrated solar thermal; CED: Cumulative energy demand; CML: CML method; $CO_{2.eq}$: $CO_{2.equivalent}$; CTU_e: Comparative toxic unit for ecosystems; CTU_h: Comparative toxic unit for humans; DALY: Disability-adjusted life years; EC: Embodied carbon; Ecological footprint: Ecological footprint method; EE: Embodied energy; EI99: Eco-indicator 99 method; EI99 PBT: Eco-indicator 99 payback time; EPBT: Energy payback time; GJ_{prim}: $GJ_{primary}$; GPBT: Greenhouse-gas payback time; GWP: Global warming potential; IMPACT 2002+: IMPACT 2002+ method; IPCC 100a: IPCC method based on a time horizon of 100 years (in terms of GWP); LCA: Life cycle assessment; PBT: Payback time; PCM: Phase change material; Pts: Points; PV: Photovoltaic; PVT: Photovoltaic/thermal; ReCiPe: ReCiPe method; ReCiPe PBT: ReCiPe payback time; (species.yr): Loss of species over a certain area (during a certain time); USEtox: USEtox method

environmental advantages in the case of nearly zero-energy buildings (Palacios-Jaimes et al., 2017).

Within the field of solar energy systems, solar thermal collectors are eco-friendly solutions towards sustainable buildings (Kalogirou, 2009; Zabalza et al., 2013; Echarri-Iribarren et al., 2018). In this context, environmental Life Cycle Assessment (LCA) on these types of systems offers interesting information. In general, LCA is considered as a useful tool for building eco-design (Zabalza et al., 2013).

Regarding LCA studies about BA solar thermal systems, Kalogirou (2009) investigated solar water heaters based on flat-plate collectors for domestic applications. Emissions (CO_2, NO_x, etc.) and Embodied Energy (EE) were examined. Kalogirou (2009) concluded that thermosiphon solar water heating systems are eco-friendly and sustainable technologies. Otanicar and Golden (2009) presented a work about emissions (CO_2, SO_x, NO_x) and EE of solar thermal collectors for domestic hot water heating. Conventional and nanofluid-based solar thermal collectors were examined. The nanofluid-based configuration presented lower embodied energy (around 9%) and about 3% higher levels in terms of pollution offsets in comparison to the conventional collector. Comodi et al. (2014) investigated traditional solar thermal collectors based on Eco-indicator 99 (EI99), Energy Payback Time (EPBT), CO_2 and economic Payback Times (PBTs). Glazed and unglazed configurations were examined. The systems were evaluated in three cities (Rome, Madrid, Munich) in order to investigate the influence of the climatic conditions on the output of the solar systems. The EPBTs ranged from 2 to 5 months in the case of the unglazed collectors and from 5 to 12 months in the case of the glazed configurations, depending on the scenario (Comodi et al., 2014). Arnaoutakis et al. (2017) evaluated, according to EI99 method, flat-plate thermosiphon and integrated-collector-storage solar water heaters. The integrated-collector-storage configuration presented a better environmental profile in comparison to the flat-plate one. Michael and Selvarasan (2017) conducted a work about LCA of different types of solar systems for domestic applications. The studied solar thermal system was based on a flat-plate collector and showed an EPBT of 0.8 years and a carbon PBT of 0.13 years. Kylili et al. (2018) examined the environmental profile of solar thermal systems with flat-plate collectors, appropriate for industrial applications. Several impact categories (Global Warming Potential (GWP), etc.) were examined. It was found that the raw material extraction and the manufacturing of the system are responsible for more than 85% of the total impact in terms of impact categories such as ozone depletion and depletion of elements. Uctug and Azapagic (2018a) investigated the environmental performance of flat-plate solar thermal collectors for domestic hot water production. The method CML 2001 was adopted. The EPBTs were calculated to be around 1 and 3.3 years, depending on the region.

Concerning LCA on BIST systems, there are few studies. With respect to LCA about gutter-integrated BIST configurations with/without Phase Change Material (PCM), some examples are following presented: 1) LCA based on Cumulative Energy Demand (CED) and GWP (Lamnatou et al., 2018a), 2) LCA according to ReCiPe, USEtox and Ecological footprint (Lamnatou et al., 2018b). The results of the study by Lamnatou et al. (2018b), according to ReCiPe endpoint single-score, showed that the configuration with PCM has 0.003 Points (Pts) per kWh of produced thermal energy higher impact in comparison to the system without PCM. Within the field of BIST LCA, additional works are those by: i) Lenz et al. (2012) about façade-integrated solar thermal collectors, ii) Lamnatou et al. (2014; 2015b; 2016) about gutter-integrated solar thermal configurations, based on EE, EPBT, Embodied Carbon (EC), IMPACT 2002+ method, etc. Lenz et al. (2012) highlighted that the credits for recycling of the metals offer a considerable (up to 30%) life-cycle impact reduction. The benefits of recycling for these types of systems have also been examined by Lamnatou et al. (2014; 2015b; 2016).

Regarding the specific category of solar thermal collectors with evacuated tubes, few LCA studies have been presented. Some examples are the works of Hang et al. (2012), Hernandez and Kenny (2012), Hoffmann et al. (2014), Carlsson et al. (2014), Greening and Azapagic (2014). The aforementioned studies compared, based on EE, EC, EPBT, Greenhouse-gas Payback Time (GPBT), EI99 method, etc., evacuated-tube with flat-plate solar thermal collectors. The results revealed that evacuated-tube collectors offer benefits from an environmental perspective. An additional article about LCA of solar thermal collectors with vacuum tubes is that presented by Lamnatou et al. (2016), consisting of two parts: 1) literature review, 2) an LCA case study about BIST systems, based on EE and EC. The review revealed that most of the vacuum-tube/BIST configurations are about façade-integrated configurations and there are few environmental LCA studies about vacuum-tube solar thermal collectors.

In relation to the issues mentioned above and by taking into account that: i) In the frame of sustainable development, vacuum-tube solar thermal collectors and BIST systems offer environmental benefits (Lamnatou et al., 2015a, 2016), ii) There is a need for more LCA studies about vacuum-tube BIST based on midpoint/endpoint life-cycle impact assessment methods as well as in terms of human toxicity and ecotoxicity (Lamnatou et al., 2015a, 2016), the present work investigates a vacuum-tube BIST system. The goals of the present study are:

1) Evaluation of environmental issues about the proposed vacuum-tube solar thermal collectors and the supplementary elements of the system based on midpoint/endpoint impact categories of ReCiPe method.

2) Calculation of the impacts related to: i) the consumption of electricity (based on different electricity mixes: France´s, Spain´s), ii) the substitution of some elements of the system during the use stage.

3) Estimation of the impacts in relation to different functional units.

4) Assessment of PBTs based on ReCiPe method - Discussion about the PBTs: i) in comparison to the lifespan of the system, ii) with/without recycling, iii) in relation to different electricity mixes.

5) Evaluation of environmental issues, about the collectors and the additional elements of the system, in terms of human toxicity and ecotoxicity, according to USEtox.

6) Assessment of the environmental profile of the proposed system based on recycling of materials which are energy-intensive and are used in large quantities.

7) Comparisons with the literature: The comparisons include several types of solar thermal collectors, multiple methods and environmental indicators on the basis of EE, EC and ReCiPe.

8) Presentation and discussion of critical issues that influence the environmental profile of BI solar systems: Different parameters such as the type of building integration, the materials of the storage system, the working fluid and the lifespan of the components are discussed.

The proposed system consists of materials that are commonly used in the frame of domestic hot water applications based on solar thermal collectors (Kalogirou, 2009; Lamnatou et al., 2015a, 2016) and, therefore, the findings of the present work can also be useful for other studies about similar types of solar thermal collectors for domestic water heating.

The structure of the present article is following presented:

- MATERIALS AND METHODS

- RESULTS – DISCUSSION
    - METHOD ReCiPe - Material manufacturing: Vacuum-tube collectors and supplementary elements of the system without recycling
    - METHOD ReCiPe – Use stage: The impacts related to the consumption of electricity
    - METHOD ReCiPe - Use stage: The impacts related to the substitutions of some elements without recycling
    - METHOD ReCiPe - The impact per m^2 of absorber and the impact per kWh of energy produced with/without recycling
    - METHOD ReCiPe – ReCiPe payback times with/without recycling
    - METHOD USEtox - Findings in terms of human toxicity and ecotoxicity with/without recycling
    - Comparisons with the literature
- BUILDING-INTEGRATED SOLAR SYSTEMS: ENVIRONMENTAL ISSUES
- CONCLUSIONS

2. MATERIALS AND METHODS

The LCA study has been conducted according to ISO 14040 (2006), ISO 14044 (2006), by considering: 1) Goal and scope definition, 2) Life-cycle inventory, 3) Life-cycle impact assessment, 4) Interpretation.

2.1. Functional units, boundaries, flows, allocation

With respect to the functional units, the results that are presented in subsections 3.1 and 3.6 refer to one solar unit that includes: 1) 16 vacuum-tube solar thermal collectors (total absorber surface: 1.8 m^2), 2) Supplementary elements of the system (storage tank of 100 *l*; tubes and their insulation; anti-freezing fluid; pump). In this way, a picture about the environmental performance of the proposed BIST, as a whole system, is provided. Moreover, in subsection 3.4 the results are presented per: i) m^2 of absorber surface, ii) kWh of thermal energy produced. Different functional units have been adopted in order to show a complete view of the environmental profile of the proposed system and, at the same time, to have more results to compare with the literature (subsection 3.7).

Regarding life-cycle calculations, the following stages have been taken into account: i) Manufacturing of the materials: Materials of the vacuum-tube solar thermal collectors and materials of the supplementary elements of the system; ii) Manufacturing of the vacuum-tube solar thermal collectors; iii) Installation: Inputs during the installation of the vacuum-tube solar thermal collectors and the supplementary elements of the system; iv) Use stage and maintenance: General maintenance and substitution of some elements during the use stage; v) Transportation of the materials according to the following routes: Factory gate → building → disposal site; vi) Disposal: End-of-life of the materials associated with the life-cycle of the system. In Figure 1, a schematic with the stages mentioned above, is presented.

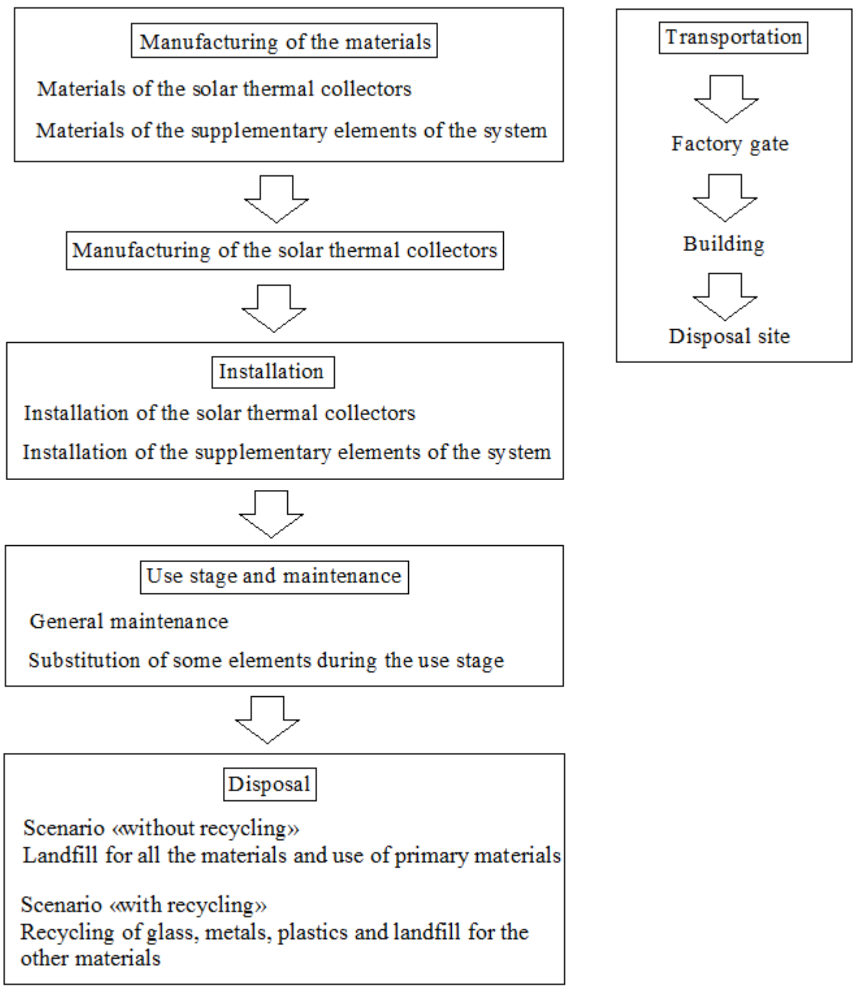


Figure 1. Present LCA study: Schematic of all the stages.

In order to focus on the effect of the materials, some graphs present results only for the manufacturing of the materials. Processes that are directly associated with manufacturing, use stage and disposal have been taken into account. The flows include acquisition of the raw materials/resources.

Allocation has been included. Allocation is defined as partitioning the flows related to the input or output of a process or a product system between the product system that is under study and one or more other product systems (ISO 14044, 2006). In the frame of the present LCA, in all the cases, the option «allocation, default - unit» has been adopted.

2.2. Inputs, outputs, assumptions, scenarios, life-cycle inventory, methods

2.2.1. Inputs and outputs

The system consists of vacuum-tube solar thermal collectors for domestic hot water heating. The collectors are integrated into the building gutters (Figure 2a). The system has two functions: 1) Production of hot water for building energy needs, 2) Rainwater evacuation. The vacuum-tubes are connected with the gutter by means of specific components. The collectors are composted by main and concentric tubes. Each main tube (Figure 2b) has two concentric copper tubes which keep the vacuum of the main tube. The heat transfer fluid enters from the larger copper tube and comes out from the smaller copper tube. There are 8 rows of 2 tubes inside the gutter (total length: 16 m). The system has been patented by Cristofari (2006). In Table 1, details about the inputs/outputs are presented. The system is appropriate for water heating in the building sector and has been tested under the Mediterranean climatic conditions of Ajaccio, in France.

a) **b)**

Figure 2. a) The BIST system (gutter-integrated) based on vacuum-tube solar thermal collectors, b) Details about the vacuum tubes (Source: Lamnatou et al., 2016).

Table 1. Inputs/outputs of the BIST vacuum-tube system. Climatic conditions: Ajaccio, France.

Annual output in terms of thermal energy (kWh/year)	Annual electricity consumption (input) for pumping (kWh/year)	Annual electricity consumption (input) for auxiliary heating (kWh/year)
1693.92	48.76	370.02

2.2.2. Assumptions, scenarios, life-cycle inventory, methods

The assumptions about general maintenance, manufacturing of the vacuum-tube solar thermal collectors, installation and transportation (total distance: 50 km) are based on the LCA study by Lamnatou et al. (2016). In Table 2, details about some additional assumptions and scenarios are presented. In Table 3, information about the substitution of some elements during the use stage can be found. In Table 4, the life-cycle inventory (Sources: SimaPro; ecoinvent) is given.

Table 2. Assumptions and scenarios.

Assumptions/scenarios	Details about the assumptions/scenarios	References – Sources of information
Scenarios in terms of the lifespan of the proposed system	20-year (pessimistic scenario) vs. 30-year (optimistic scenario) lifespan	Kalogirou (2009); Lamnatou et al., (2016)
Assumption in terms of the lifespan output (hot water production) of the proposed system	The output of the first year is the same with the output of the last year	Lamnatou et al. (2018a)
Scenarios in terms of the disposal (end-of-life)	Two scenarios: i) Landfill for all the materials and use of primary materials (scenario «without recycling»), ii) Recycling of glass, metals, plastics and landfill for the other materials (scenario «with recycling»)	Lamnatou et al. (2018a); Lamnatou et al. (2016)
Assumption: Use of an electric-resistance water heater with an efficiency of 95% and France´s electricity mix	Environmental impact that is prevented because of the utilisation of the energy produced by the solar thermal system (instead of using a conventional water heating system in order to produce the same	Reference for the electric-resistance water heater: Smarter HOUSE; References for the electricity

	amount of energy)	mix: SimaPro; ecoinvent; In the literature electric auxiliary heaters for domestic solar thermal collectors have been adopted, for instance by Kalogirou (2009) and Hang et al. (2012)
Scenarios in terms of the electricity mixes: Two different electricity mixes have been examined because some environmental indicators are remarkably influenced by the electricity mix of a country	France´s and Spain´s electricity mixes have been examined; The scenario of Spain´s electricity mix is theoretical since the proposed system has been developed and tested in France	SimaPro; ecoinvent

Table 3. Substitutions of some elements during the use stage. Scenarios in terms of system lifespan: i) 30 years, ii) 20 years.

Elements that are replaced	30-year lifespan: Times of replacement	20-year lifespan: Times of replacement
Glass of the vacuum tubes	2	1
Copper of the vacuum tubes	2	1
Aluminium of the vacuum tubes	2	1
Polyethylene of the collectors	6	4
Rock wool of the storage tank	1	1
Stainless steel of the storage tank	1	1
Propylene glycol (anti-freezing fluid)	5	3

Table 4. Life-cycle inventory for the whole system (16 solar thermal collectors and additional components of the system): Lamnatou et al. (2016).

Materials of the 16 solar thermal collectors	Mass (kg)
Vacuum tubes (material: glass)	20.23
Flat-plate absorber (material: aluminium)	1.88
Support of the absorber (material: aluminium)	0.03
External tube/vacuum tube (material: copper)	4.50
Internal tube/vacuum tube (material: copper)	2.25
Collector in the gutters (material: copper)	7.88
Collector insulation (material: polyethylene)	1.14
External case/gutter (material: aluminium)	10.58
Gutter lacquer (material: polyester)	0.15
Materials of the additional components of the BIST system	**Mass (kg)**
Storage tank: metallic part (material: stainless steel)	12.48
Storage tank: insulation (material: rock wool)	4.08
Tubes: metallic part (material: copper)	5.64
Tubes: insulation (material: polyurethane)	1.80
Anti-freezing fluid (material: propylene glycol)	1.40

Pump: metallic part (material: stainless steel)	3.00

With respect to the methods, «ReCiPe Endpoint (H) V1.10 / Europe ReCiPe H/A» and «ReCiPe Midpoint (H) V1.10 / Europe Recipe H» have been adopted (Sources: SimaPro; ecoinvent). In addition, ReCiPe Payback Time (ReCiPe PBT) (Lamnatou et al., 2017) has been evaluated:

$$\text{ReCiPe PBT} = \frac{I_{mat} + I_{inst} + I_{transp} + I_{disp}}{I_{out.a} - I_{O\&M.a}} \qquad (years) \tag{1}$$

Where I is the total ReCiPe endpoint single-score (in Pts) in terms of: I_{mat} that is the impact during the manufacturing of the materials (collectors; supplementary elements of the system) and manufacturing of the collectors; the impact associated with installation (I_{inst}), transportation (I_{transp}) and disposal (I_{disp}); the impact that is prevented (on an annual basis) due to the use of the thermal energy that is produced by the solar thermal system instead of using electricity from the national grid in order to produce the same amount of thermal energy by means of an electric-resistance water heater ($I_{out.a}$); the impact (on an annual basis) during the use stage ($I_{O\&M.a}$), in this case the inputs for the substitutions of some elements of the system and the general maintenance have been taken into account (on an annual basis). In the literature, ReCiPe PBT has been adopted for instance by Akyüz et al. (2017). Moreover, in the same concept, EI99 PBT has been evaluated by Jungbluth (2005).

ReCiPe method has been used because it combines midpoint and endpoint impact categories, giving useful information for multiple issues such as: 1) climate change, ozone depletion, freshwater eutrophication, human toxicity and fossil depletion (midpoint level), 2) human health, ecosystems and resources (endpoint level). In the literature, ReCiPe method has been adopted in order to evaluate the environmental sustainability of BIST systems (Lamnatou et al., 2017, 2018b), proving the usefulness of this method in the frame of energy production and sustainable development.

USEtox (default) V1.03 / Europe 2004 method has also been adopted in order to evaluate the impacts related to human toxicity and ecotoxicity. In the literature, USEtox has been used in the frame of LCA on BIST systems (Lamnatou et al., 2018b). In the work of Rosenbaum et al. (2011), details about USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in LCA can be found.

The sources for the methods mentioned above and for the life-cycle inventory are the following: SimaPro 8, ecoinvent 3. SimaPro is a software which contains a number of life-cycle impact assessment methods that are utilised in order to calculate impact assessment results (PRé, 2014). Ecoinvent is a comprehensive, transparent and international database with multiple life-cycle inventory datasets (Source: ecoinvent).

3. RESULTS – DISCUSSION

3.1. METHOD ReCiPe - Material manufacturing: Vacuum-tube collectors and supplementary elements of the system without recycling

3.1.1. ReCiPe endpoint approach – single score

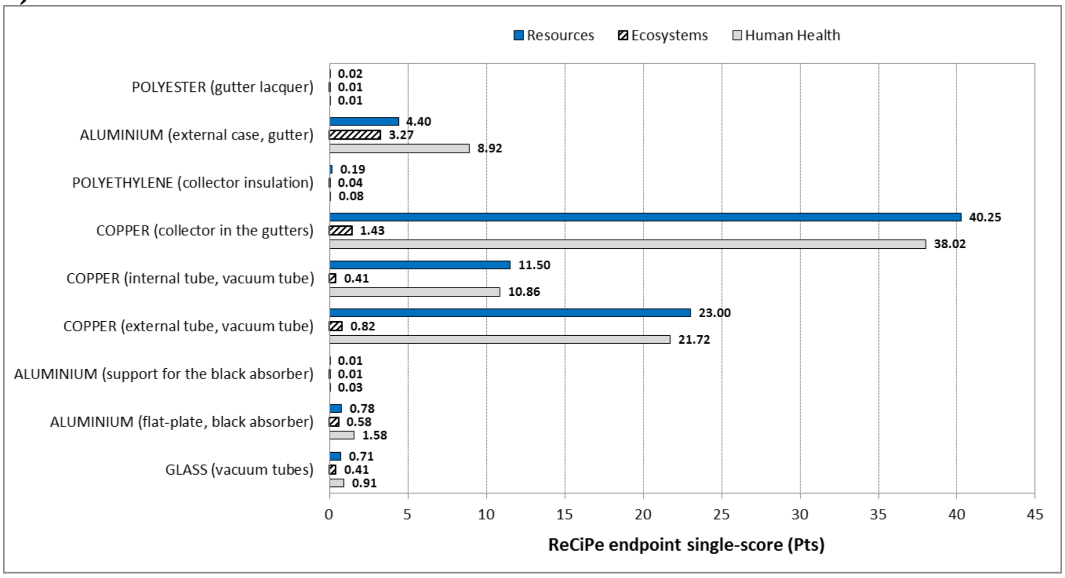
In Figure 3, ReCiPe endpoint/single-score findings are presented. Figure 3a is about the material manufacturing of the vacuum-tube collectors. Figure 3b refers to the material manufacturing of the supplementary elements of the system. The results show that:

1) In both cases (collectors; supplementary elements of the system) copper is the material with the highest scores. By taking into account the results of both cases, copper shows a total score of 205 Pts, including the three endpoint categories of ReCiPe (Human health, Ecosystems and Resources). The value of 205 Pts is remarkably higher than the total scores of the other materials which range from 0.04 to 20 Pts. Moreover, aluminium and stainless steel present the second and third highest impact with total scores of 20 and 17 Pts, respectively.

2) By taking into account all the studied cases of Figure 3, it can be noticed that the endpoint category of Ecosystems presents considerably lower impact in comparison to the categories of Human health and Resources. These differences are particularly pronounced in the case of copper, ranging from 10 to 39 Pts.

3) The materials polyester, polyethylene, glass, propylene glycol, polyurethane and rock wool present total scores, including the three endpoint categories of ReCiPe (Human health, Ecosystems and Resources), which range from 0.04 Pts (polyester) to 2.03 Pts (glass).

a)



b)

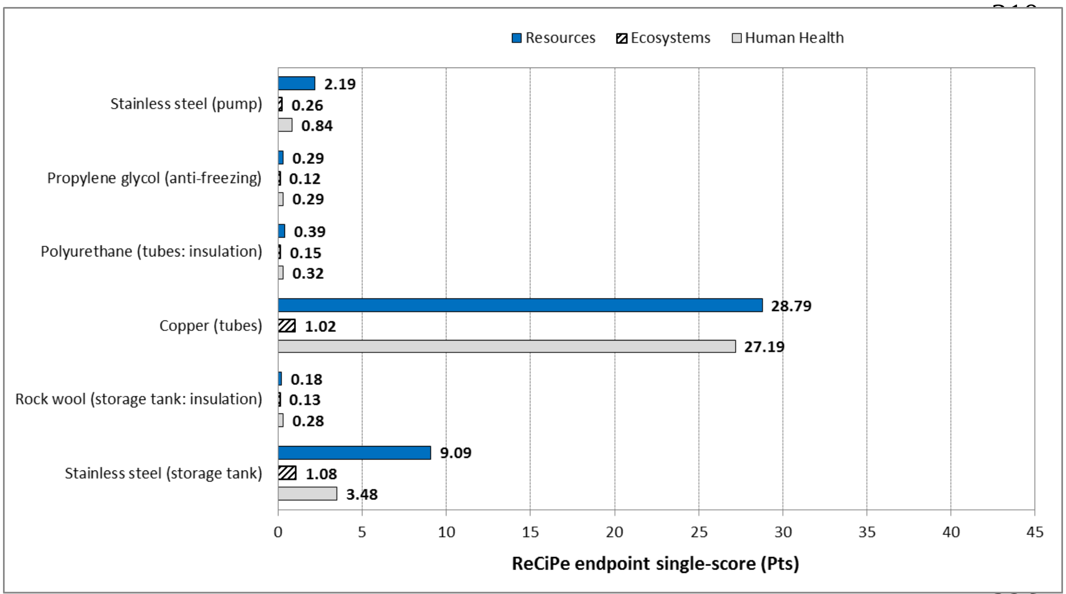


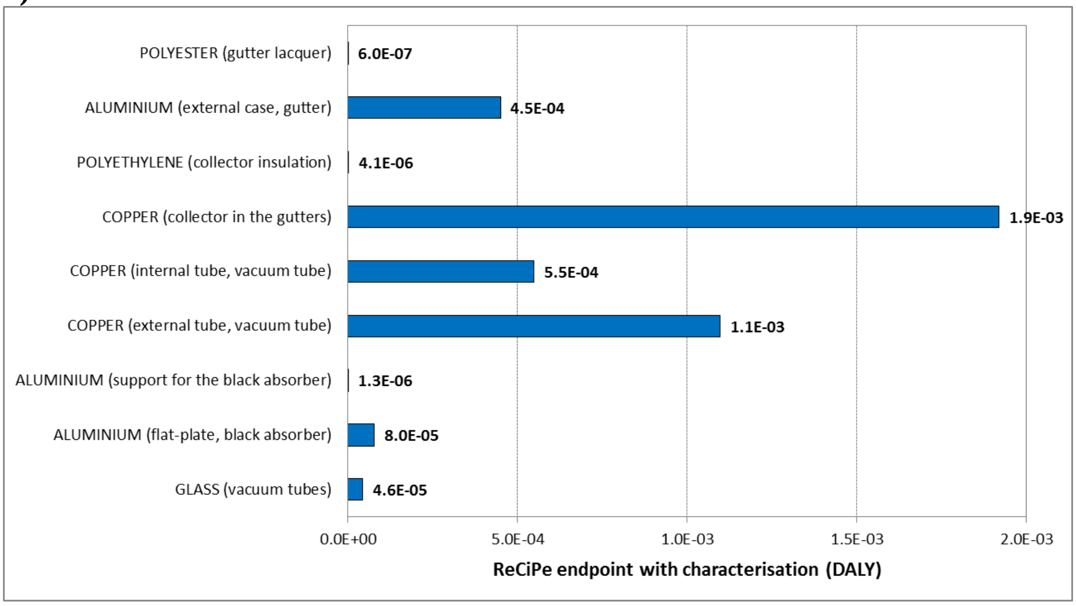
Figure 3. ReCiPe endpoint single-score. Material manufacturing of: a) the 16 vacuum-tube collectors, b) the supplementary elements of the system. Scenario «without recycling».

3.1.2. ReCiPe endpoint approach – with characterisation

Based on ReCiPe endpoint with characterisation, Figures 4 and 5 show the results in terms of DALY and (species.yr), respectively. Figures 4a and 5a refer to the material manufacturing of the 16 vacuum-tube collectors. Figures 4b and 5b are about the supplementary elements of the system.

Figure 4 shows that copper is responsible for the highest DALY with a total value of 0.005 DALY for both the collectors and the additional components of the system. Aluminium and stainless steel present the second and third highest DALY with total values of 0.0005 and 0.0002 DALY, respectively. In addition, from Figure 5 it can be seen that copper and aluminium are the materials with the highest impacts in terms of (species.yr) with a total value of 1.7E-06 (species.yr) for each material (copper; aluminium) by considering both the collectors and the supplementary elements of the system. The other materials (except of aluminium, copper and stainless steel) present total values ranging from 6.0E-07 (polyester) to 4.6E-05 (glass) DALY (Figure 4) and from 4.1E-09 (polyester) to 1.9E-07 (glass) (species.yr) (Figure 5).

a)



b)

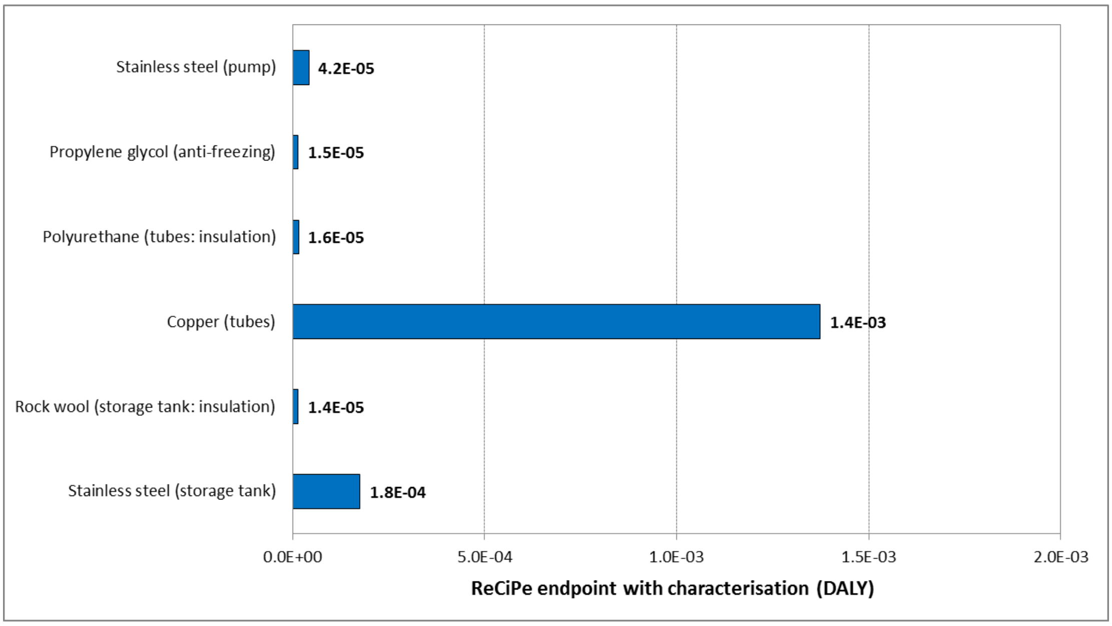
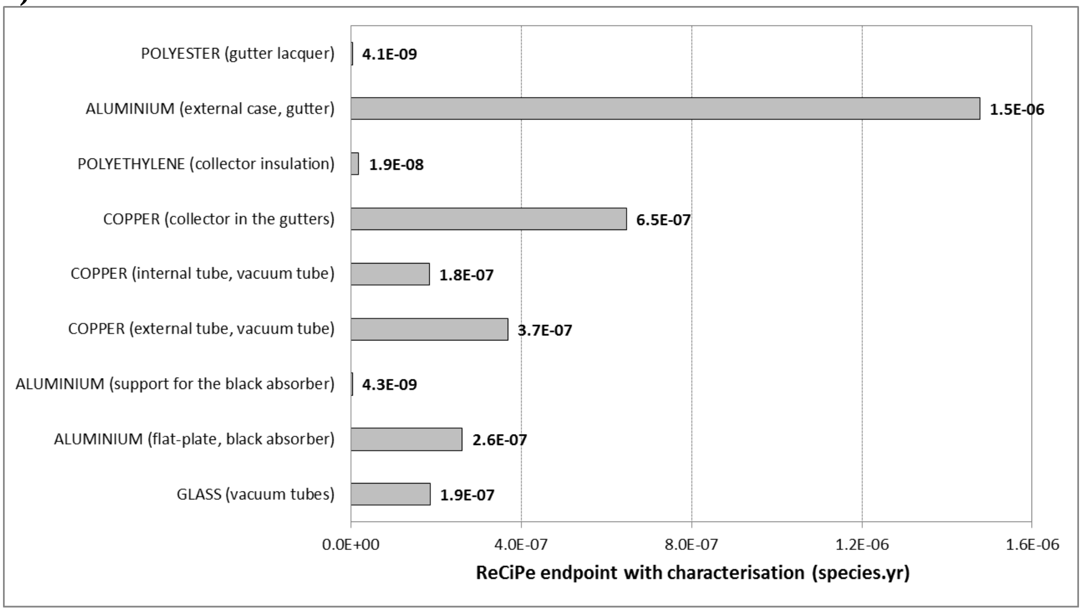


Figure 4. ReCiPe endpoint with characterisation (DALY). Material manufacturing of: a) the 16 vacuum-tube collectors, b) the supplementary elements of the system. Scenario «without recycling».

a)



b)

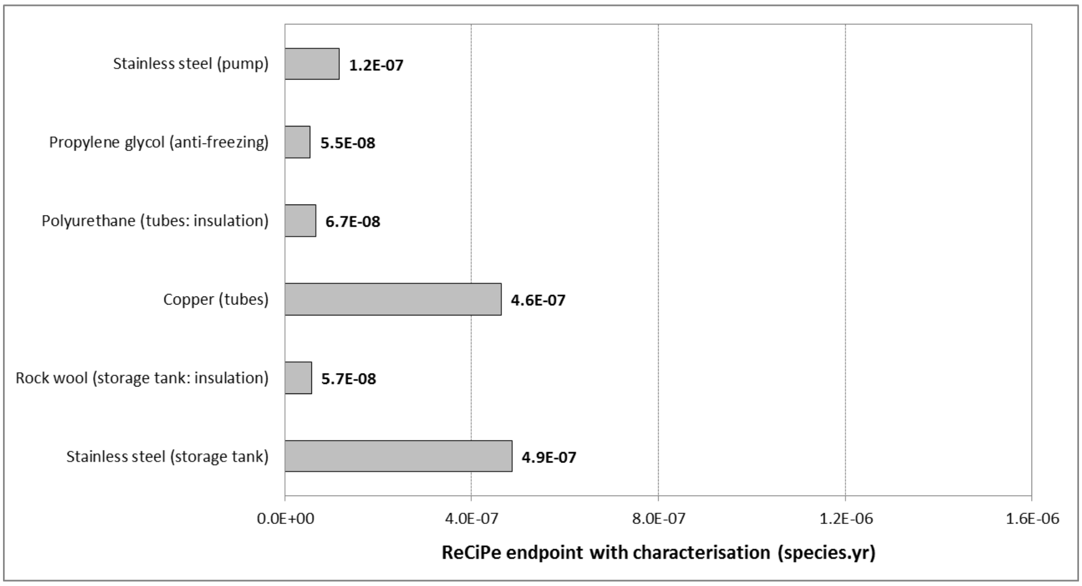


Figure 5. ReCiPe endpoint with characterisation (species.yr). Material manufacturing of: a) the 16 vacuum-tube collectors, b) the supplementary elements of the system. Scenario «without recycling».

3.1.3. Discussion about ReCiPe/endpoint results and the role of recycling

The findings according to ReCiPe endpoint single-score «with characterisation», demonstrate that copper, aluminium and stainless steel are the materials with the highest scores. In the case of copper, the impact is mainly related to copper concentrate for the production of primary copper. Concerning aluminium, its impact is mainly associated with the following inputs: electricity, medium as well as high voltage, for the production of liquid aluminium and, then, primary aluminium. In terms of steel, the major part of its impact is because of the production of ferrochromium and ferronickel (Sources: SimaPro; ecoinvent).

Figures 3-5 are based on primary materials. By means of recycling of the metals, considerable reduction of the environmental impact of the system can be achieved.

In the literature, different techniques for aluminium, copper and steel recycling have been examined (Samuelsson and Björkman, 2014; Soo et al., 2018). By placing emphasis on the use of aluminium and steel in the building sector, Meneghelli (2018) noted that these two materials are extensively adopted in buildings and the CO_2 emissions during manufacturing include environmental impacts that should be taken into account as a part of the EC of the whole building.

In the frame of the present study, for the end-of-life and based on ReCiPe endpoint single-score, calculations which include recycling of glass, metals and plastics have been conducted. The calculations include both scenarios 30-year and 20-year lifespan. The results reveal that aluminium, copper and stainless steel are the materials with the first (58-59%), second (17-19%) and third (16-18%) highest contributions to the reduction in the impact due to recycling.

In addition, the benefits of recycling have been examined according to ReCiPe midpoint with characterisation. The results verify the considerable reduction in the total impact, mainly due to the recycling of the metals. More analytically, based on ReCiPe midpoint with characterisation, aluminium recycling shows contributions with percentages more than 51% in all the midpoint categories except of Metal depletion. Moreover, copper and stainless steel present percentages ranging from 25% to 54% for the categories of Ozone depletion and Metal depletion.

The scenario «with recycling» has been investigated because the proposed system, and in general many types of solar thermal collectors for domestic applications, consist of large amounts of metals. This means that these types of systems present high recycling potential. Therefore, the scenario «without recycling» has been examined in order to compare two extreme cases, with/without recycling, and highlight the environmental benefits of recycling in the case of solar thermal collectors for domestic applications.

3.1.4. ReCiPe midpoint approach with characterisation: Results and discussion

Subsection 3.1.4 presents results based on ReCiPe midpoint with characterisation. In Table 5 (and in Table 6) the parts of the 16 vacuum-tube collectors and the supplementary elements of the system that according to ReCiPe endpoint single-score show total scores more than 2 Pts have been included. The results are presented as total values for each material. In Table 5 (and in Table 6) «stainless steel» represents the steel of the storage tank and the pump, «copper» refers to the vacuum-tube collectors (external/internal tubes and gutter) and the tubes of the supplementary elements of the system, «aluminium» represents the flat-plate absorber as well as the external case of the gutter, «glass» refers to the glass of the vacuum tubes of the collectors. The findings of Table 5 (and those of Table 6) are based on the scenario «without recycling».

Copper has the highest impact in 15 out of the 18 midpoint categories. Furthermore, for the categories of Freshwater eutrophication, Marine Eutrophication, Human toxicity, Freshwater ecotoxicity, Marine ecotoxicity and Metal depletion, copper presents percentages higher than 91% of the total impact that includes glass, aluminium, copper and stainless steel. Moreover, the results verify that in terms of Terrestrial acidification, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Urban land occupation and Natural land transformation, copper shows percentages ranging from 54% to 78%. By considering that ReCiPe method includes connections between midpoint and endpoint categories (PRé, 2014), it can be seen that most of the midpoint categories cited above in the analysis of copper impact, at endpoint level are related to damages to ecosystems and human health.

Aluminium presents the highest impact for the categories of Climate change, Ozone depletion and Fossil depletion with percentages ranging from 38% to 50% of the total impact that includes glass, aluminium, copper and stainless steel.

Discussion in terms of each midpoint category (Tables 5 and 6):

- Climate change: Aluminium shows almost double impact in comparison to copper.
- Ozone depletion: The score of aluminium is a little higher than the one of copper.
- Terrestrial acidification: Copper presents 0.9 kg SO_2 eq higher impact in comparison to aluminium.
- Freshwater eutrophication: Copper shows a score which is around 30 times higher comparing to that of aluminium.
- Marine eutrophication: Copper presents an impact about 4.5 kg N eq higher than the one of aluminium.
- Human toxicity: Copper shows a score which is approximately 56 times higher than that of aluminium.
- Photochemical oxidant formation: Copper has almost double impact in comparison to aluminium.
- Particulate matter formation: Copper presents an impact which is around 3 times that of aluminium.
- Terrestrial ecotoxicity: The score of copper is around 0.04 kg 1,4-DB eq higher comparing to that of aluminium.

- Freshwater ecotoxicity: The impact of copper is about 40 times higher in comparison to that of aluminium.

- Marine ecotoxicity: Copper shows a score which is approximately 37 times higher comparing to that of aluminium.

- Ionising radiation: The impact of copper is almost double of that of aluminium.

- Agricultural land occupation: Copper presents around 4 m^2a higher score than aluminium.

- Urban land occupation: Copper shows about 10 m^2a higher score in comparison to aluminium.

- Natural land transformation: The value of copper is double than that of aluminium.

- Water depletion: Copper presents approximately 444 m^3 more than aluminium.

- Metal depletion: Copper shows a score that is around 537 times higher than that of aluminium.

- Fossil depletion: Aluminium presents about 15 kg oil eq higher than copper.

Table 5. ReCiPe midpoint with characterisation: Components of the BIST system based on: Glass, aluminium, copper and stainless steel. Scenario «without recycling».

ReCiPe midpoint category	**Units for each category**	**GLASS**	**ALUMINIUM**	**COPPER**	**STAINLESS STEEL**
Climate change	kg CO_2 eq	21.05	205.88	122.12	63.66
Ozone depletion	kg CFC-11 eq	1.5E-06	6.5E-06	6.4E-06	2.8E-06
Terrestrial acidification	kg SO_2 eq	0.17	1.43	2.33	0.40
Freshwater eutrophication	kg P eq	0.003	0.12	3.59	0.02
Marine eutrophication	kg N eq	0.01	0.04	4.56	0.01
Human toxicity	kg 1,4-DB eq	3.45	110.06	6128.75	55.45
Photochemical oxidant formation	kg NMVOC	0.11	0.72	1.59	0.26
Particulate matter formation	kg PM10 eq	0.05	0.64	1.85	0.35
Terrestrial ecotoxicity	kg 1,4-DB eq	0.001	0.01	0.05	0.02
Freshwater ecotoxicity	kg 1,4-DB eq	0.09	2.99	120.26	5.97

Marine ecotoxicity	kg 1,4-DB eq	0.09	2.93	109.87	6.15
Ionising radiation	kBq U235 eq	1.63	9.14	18.28	8.07
Agricultural land occupation	m^2a	1.06	2.62	6.29	4.29
Urban land occupation	m^2a	0.14	1.89	12.36	1.43
Natural land transformation	m^2	0.01	0.02	0.04	0.01
Water depletion	m^3	26.94	1820.78	2264.98	1762.12
Metal depletion	kg Fe eq	2.35	4.03	2163.73	205.08
Fossil depletion	kg oil eq	5.61	46.61	31.44	16.59

Table 6. Based on the results presented in Table 5, the material with the highest impact in each midpoint category is indicated with X.

ReCiPe midpoint category	**Units for each category**	**GLASS**	**ALUMINIUM**	**COPPER**	**STAINLESS STEEL**
Climate change	kg CO2 eq		X		
Ozone depletion	kg CFC-11 eq		X		
Terrestrial acidification	kg SO2 eq			X	
Freshwater eutrophication	kg P eq			X	
Marine eutrophication	kg N eq			X	
Human toxicity	kg 1,4-DB eq			X	
Photochemical oxidant formation	kg NMVOC			X	
Particulate matter formation	kg PM10 eq			X	
Terrestrial ecotoxicity	kg 1,4-DB eq			X	
Freshwater ecotoxicity	kg 1,4-DB eq			X	
Marine ecotoxicity	kg 1,4-DB eq			X	
Ionising radiation	kBq U235 eq			X	
Agricultural land occupation	m^2a			X	
Urban land occupation	m^2a			X	
Natural land transformation	m^2			X	
Water depletion	m^3			X	
Metal depletion	kg Fe eq			X	
Fossil depletion	kg oil eq		X		

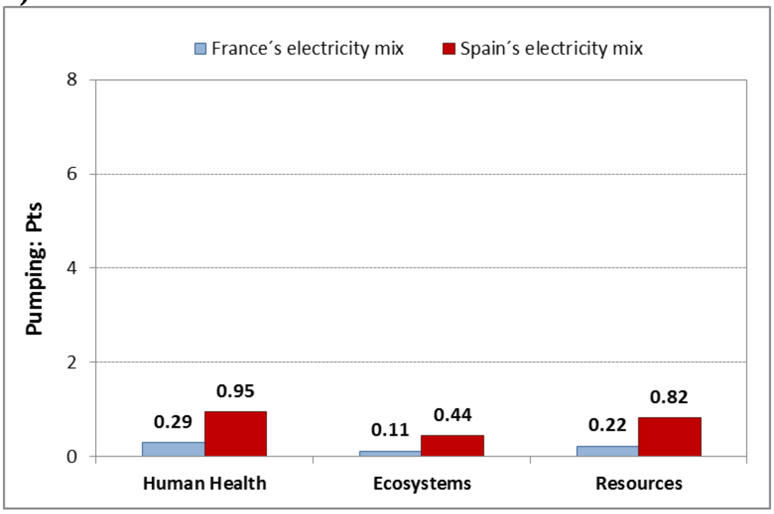
3.2. METHOD ReCiPe – Use stage: The impacts related to the consumption of electricity

In Figure 6, ReCiPe endpoint/single-score impacts (in Pts) associated with pumping (Figure 6a) and auxiliary heating (Figure 6b) are illustrated. From Figure 6 it can be noted that there is a remarkable difference between France´s and Spain´s scenario, especially for Human health and Resources. More analytically, the hypothetical scenario based on Spain´s electricity mix shows 1.59 and 12.08 Pts higher impact, for pumping and auxiliary heating respectively, in comparison to the case of France´s electricity mix. These findings can be interpreted based on the characteristics of the electricity mixes of Spain and France. In Spain (year: 2017), the coverage of the peninsular electricity demand included the following sources of energy: 21.5% nuclear, 17.0% carbon, 13.9% combined cycle, 11.0% cogeneration, 1.2% waste, 18.2% wind power, 7.0% hydraulic power, 3.1% Photovoltaic (PV) systems, 2.1% solar thermal systems, 1.4% other renewable energy sources, 3.6% international exchanges (Source: El Sistema Eléctrico Español, AVANCE, 2017). Regarding France (year: 2017), the total electricity production included 71.6% nuclear, 10.3% fossil fuel (thermal), 4.5% wind power, 1.7% solar energy, 10.1% hydraulic power, 1.7% bioenergy (Source: Réseau de Transport d'Électricité (RTE), France, 2017).

Based on the data presented above, it can be seen that there are substantial differences between the compositions of the two electricity mixes. Especially in terms of nuclear energy, in Spain the percentage is 21.5% whereas in France the percentage is 71.6%. The high penetration of nuclear energy in French electricity generation mix influences some environmental indicators. It is known that nuclear energy has low greenhouse-gas emissions; however, there are drawbacks such as concerns about the availability of uranium in the future, management and disposal of the waste that is produced and safety in case of potential accidents (Report NEEDS, 2007). More analytically, in the report NEEDS (2007), the following weak points/barriers of nuclear development were presented: 1) Risk of severe accidents, 2) Waste management, 3) Potential risk of proliferation, 4) Financial risks, 5) Controversial social acceptability.

In subsection 3.7, an additional discussion about the effect of the electricity generation mix, in relation to some environmental indicators, is provided.

a)



b)

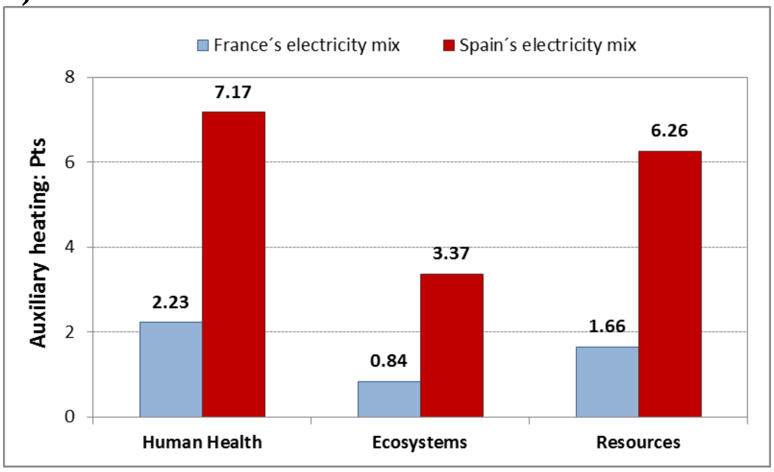


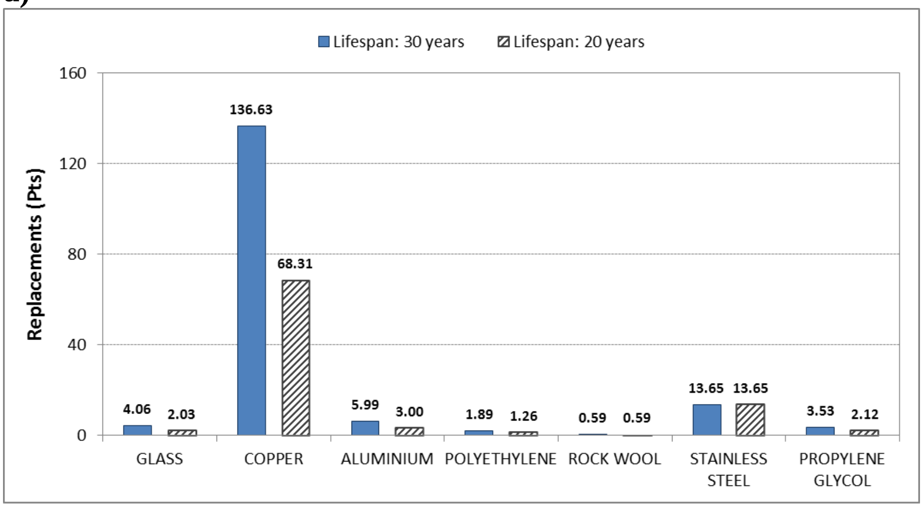
Figure 6. ReCiPe (endpoint, single-score) for: a) Pumping, b) Auxiliary heating. France´s electricity mix and Spain´s electricity mix (hypothetical scenario).

3.3. METHOD ReCiPe - Use stage: The impacts related to the substitutions of some elements without recycling

Figure 7 presents the scores related to the replacements of some materials during the use stage, in terms of Pts (Figure 7a), DALY (Figure 7b) and (species.yr) (Figure 7c). The calculations are for the scenario «without recycling». The findings reveal that:

1) In all the cases (Pts; DALY; species.yr), copper is the material with the highest impacts. Especially based on Pts and DALY, there is a considerable difference between the scores of copper and those of the other materials.
2) With respect to (species.yr), copper, aluminium and stainless steel are the materials with the three highest impacts.
3) By focusing on the lifespan effect, in certain cases there are remarkable differences between the two scenarios of 30-year and 20-year lifespan. For instance, based on Pts and DALY, the more pronounced difference between the two lifespans can be seen in the case of copper: around 68 Pts and 1.7E-03 DALY.

a)



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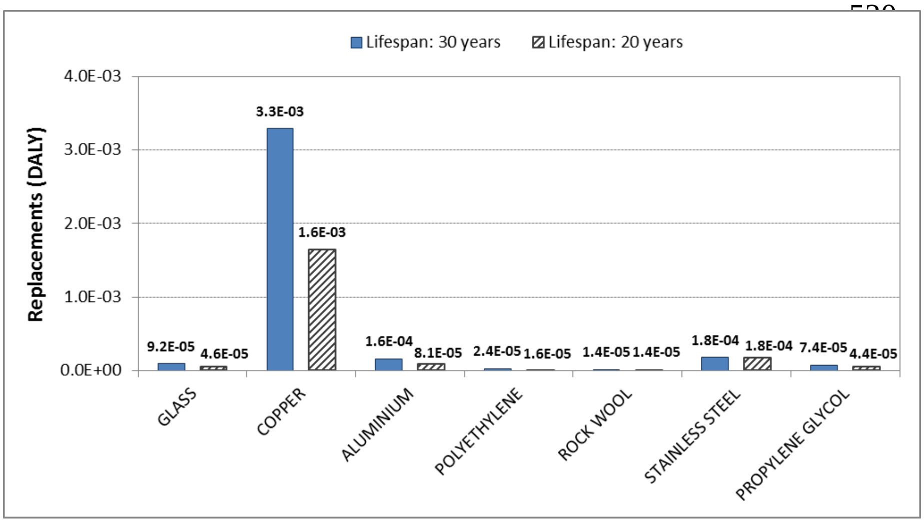


c)

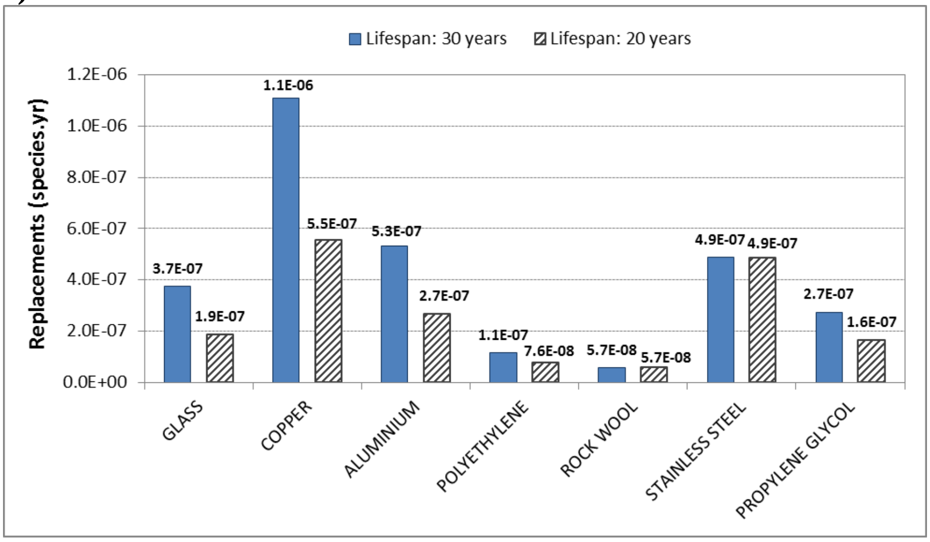


Figure 7. Results according to: a) ReCiPe endpoint single-score (Pts), b) ReCiPe endpoint with characterisation (DALY), c) ReCiPe endpoint with characterisation (species.yr). Replacements of some materials during the use stage: 30-year and 20-year lifespan. Scenario «without recycling».

3.4. METHOD ReCiPe - The impact per m^2 of absorber and the impact per kWh of energy produced with/without recycling

By taking into account only the manufacturing of the materials of the collectors and the manufacturing of the collectors, and based on ReCiPe endpoint/single-score and the scenario «without recycling», an impact of 121 Pts per m^2 of absorber was found.

In addition, calculations about the life-cycle impact per m^2 of absorber and per kWh of thermal energy produced have been done. ReCiPe endpoint single-score and scenarios with/without recycling have been adopted. The following life-cycle stages have been taken into account:

- Manufacturing of the materials of the collectors and manufacturing of the collectors.
- Manufacturing of the additional components of the system.
- Transportation.
- Installation.
- Disposal.
- Operation and maintenance, except of pumping and auxiliary heating.

In Table 7, the results are presented. It can be seen that:

1) Without taking into account recycling, the impacts are 0.010-0.012 Pts/kWh and 230-273 Pts/m^2.

2) Recycling offers an impact reduction of 0.001 Pts/kWh and 22-25 Pts/m^2.

3) There is a difference of around 0.002 Pts/kWh and 40-43 Pts/m^2 between the 20-year and the 30-year lifespan.

Table 7. ReCiPe endpoint single-score life-cycle impacts (in Pts) per kWh of produced thermal energy and per m^2 of absorber.

Lifespan	Scenario WITHOUT recycling	Scenario WITH recycling	Impact reduction due to recycling
20 years	0.012 Pts/kWh	0.011 Pts/kWh	0.001 Pts/kWh
30 years	0.010 Pts/kWh	0.009 Pts/kWh	0.001 Pts/kWh
20 years	230 Pts/m^2	208 Pts/m^2	22 Pts/m^2
30 years	273 Pts/m^2	248 Pts/m^2	25 Pts/m^2

3.5. METHOD ReCiPe – ReCiPe payback times with/without recycling

ReCiPe PBTs according to different scenarios (France´s and Spain´s electricity mix; With/without recycling) have been evaluated. For the calculation of the impacts related to transportation, disposal and the annual inputs during the use stage, the scenario of 30-year lifespan has been taken into account. For the evaluation of the annual impact during the use stage, the inputs for the substitutions of some elements and the general maintenance have been taken into account, having as reference an annual basis. ReCiPe PBT is: i) an alternative PBT beyond the classic PBTs which place emphasis on primary energy (EPBT) and GHGs (GPBT), ii) based on the total single-score (endpoint) in Pts. In the same way with EPBT and GPBT, the lower the ReCiPe PBT the faster the system will offset the environment impact associated with its life-cycle.

The findings (Figure 8) reveal that: 1) Recycling results in ReCiPe-PBT reduction of 2.66 and 0.59 years in the case of France and Spain, respectively, 2) There is a considerable reduction (around 12-14 years) in ReCiPe PBT by adopting Spain´s instead France´s electricity mix. More analytically, for the scenario «without recycling», ReCiPe PBT is 18.14 years in the case of France and 4.03 years in the case of Spain.

By assuming a system lifespan of 30 years (optimistic scenario), it can be seen that: 1) In both cases (France; Spain), ReCiPe PBTs are much lower than the lifespan of the system, 2) The hypothetical scenario based on Spain´s electricity mix offers a ReCiPe PBT around 26 years lower than the lifespan of the system (scenario «without recycling»), 3) The scenario according to French electricity mix presents a ReCiPe PBT around 12 years lower than the lifespan of the system (scenario «without recycling»). Certainly, these considerable differences between the two cases (Spain; France) are mainly related to the characteristics of the two electricity mixes that have been analytically presented and discussed in subsection 3.2. In subsection 3.7, an additional discussion about this issue is provided.

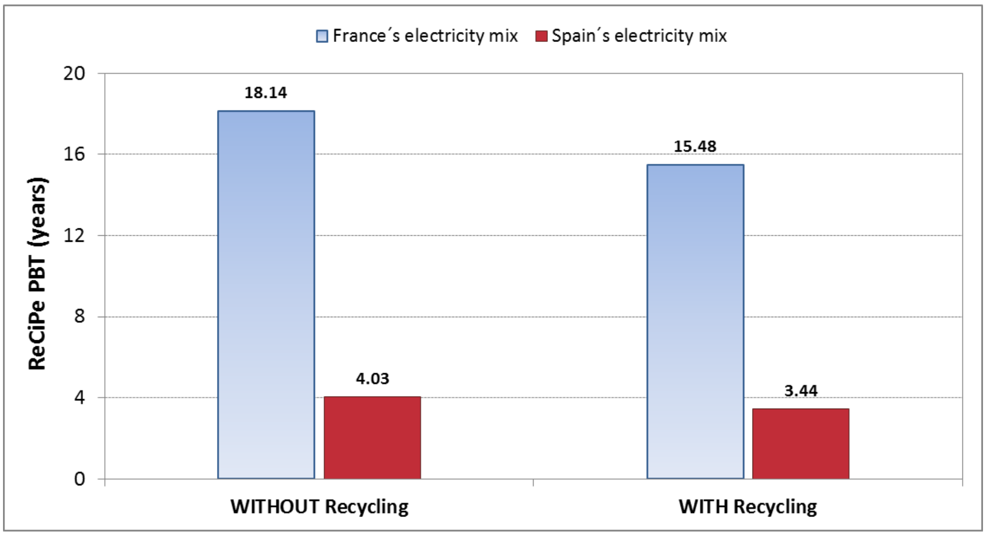


Figure 8. ReCiPe PBT in years. Cases: With/without recycling; France´s electricity mix and Spain´s electricity mix (hypothetical scenario).

3.6. METHOD USEtox - Findings in terms of human toxicity and ecotoxicity with/without recycling

Figures 9 and 10 present the USEtox results in terms of material manufacturing/scenario «without recycling» for the 16 vacuum-tube collectors and the additional elements of the system, respectively. From these figures it can be noted that:

1) Concerning human toxicity cancer and non-cancer of the collectors (Figure 9a), the aluminium for the external case of the gutter and the copper for the collector in the gutter and for the external tubes of the vacuum tubes are the parts of the collectors with the three highest impacts.

2) Regarding ecotoxicity of the collectors (Figure 9b), the three copper-based components show the three highest scores with values ranging from 0.23 to 0.80 CTU_e.

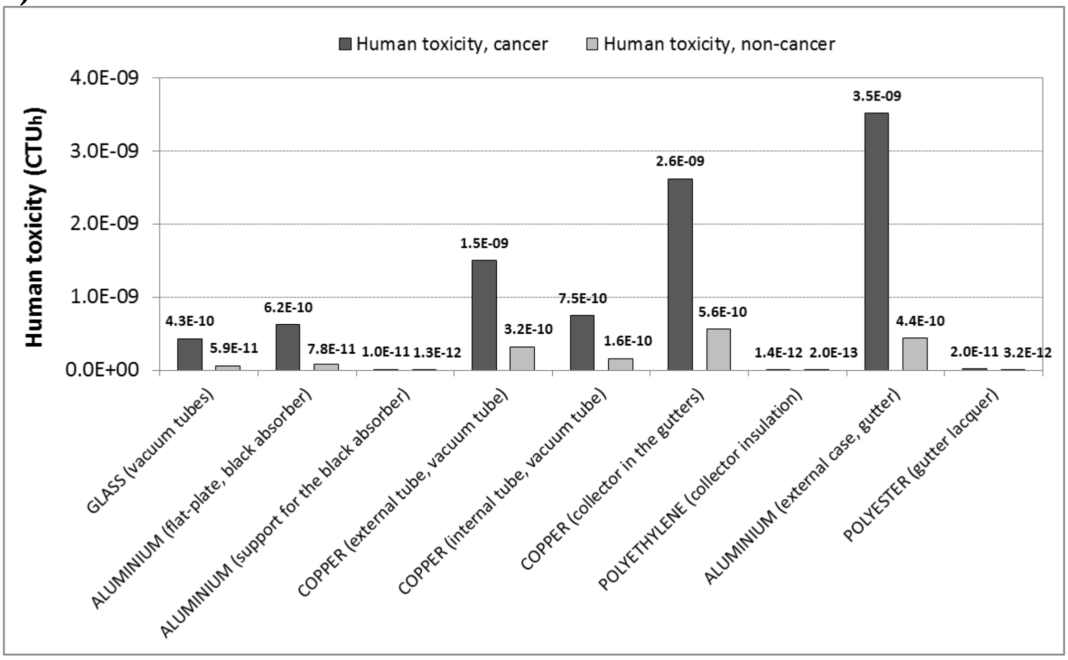
3) With respect to human toxicity/cancer of the additional elements of the system (Figure 10a), the stainless steel for the storage tank, the propylene glycol and the copper for the tubes are the components with the three highest impacts. Furthermore, the findings about human toxicity/non-cancer (Figure 10b) reveal that the propylene glycol is the material with the highest score, presenting a value of 4.0E-08 CTU_h, considerably higher in comparison to the other materials.

4) Concerning ecotoxicity of the additional elements of the system (Figure 10b), the three highest scores are the following: copper for the tubes, rock wool for the insulation of the storage tank and stainless steel for the storage tank, showing values which range from 0.28 to 0.57 CTU_e.

5) By taking into account both the collectors and the additional elements of the system (Figures 9 and 10), it can be seen that the material with the highest score in terms of: i) human toxicity/cancer is copper (total score: 6.7E-09 CTU_h), ii) human toxicity non-cancer is propylene glycol (total score: 4.0E-08 CTU_h), iii) ecotoxicity is copper (total score: 2.06 CTU_e).

The findings presented above (Figures 9 and 10) are based on the use of primary materials during material manufacturing. For the disposal and by taking into account the materials of the collectors, the additional elements of the system as well as the materials that are replaced over system lifespan, calculations which include recycling of glass, metals and plastics have been conducted. With respect to system lifespan, two scenarios, 30-year and 20-year lifespan, have been examined. According to USEtox, the results demonstrate that by adopting recycling of aluminium, copper and steel, a considerable reduction in the environmental impact can be achieved. By placing emphasis on the impact reduction in each of the three impact categories of USEtox (human health/cancer, human health/non-cancer, ecotoxicity), the findings verify that there is a decrease in the impact which ranges from 20% to 95%, depending on the type of the metal and the impact category.

a)



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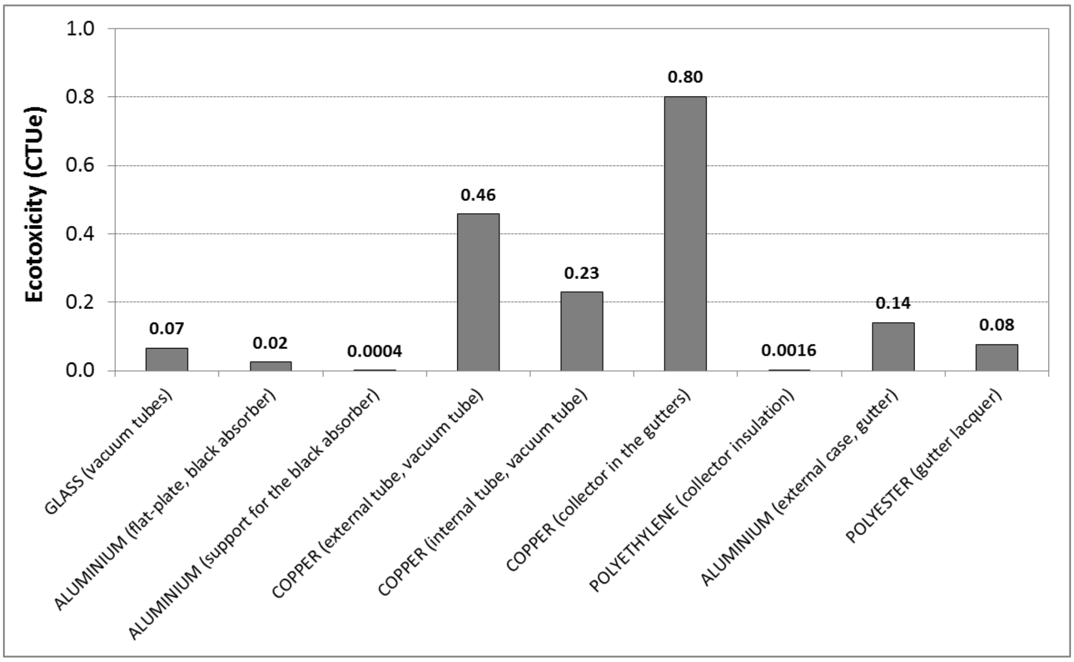
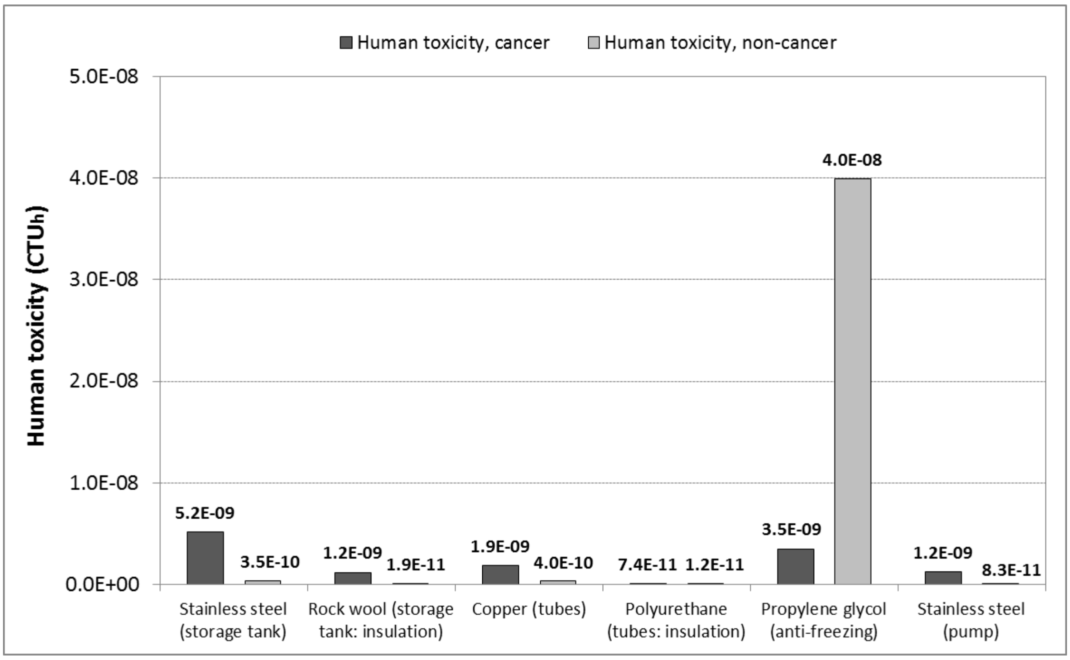


Figure 9. USEtox. Material manufacturing of the 16 vacuum-tube collectors in terms of: a) Human toxicity (cancer and non-cancer), b) Ecotoxicity. Scenario «without recycling».

a)



b)

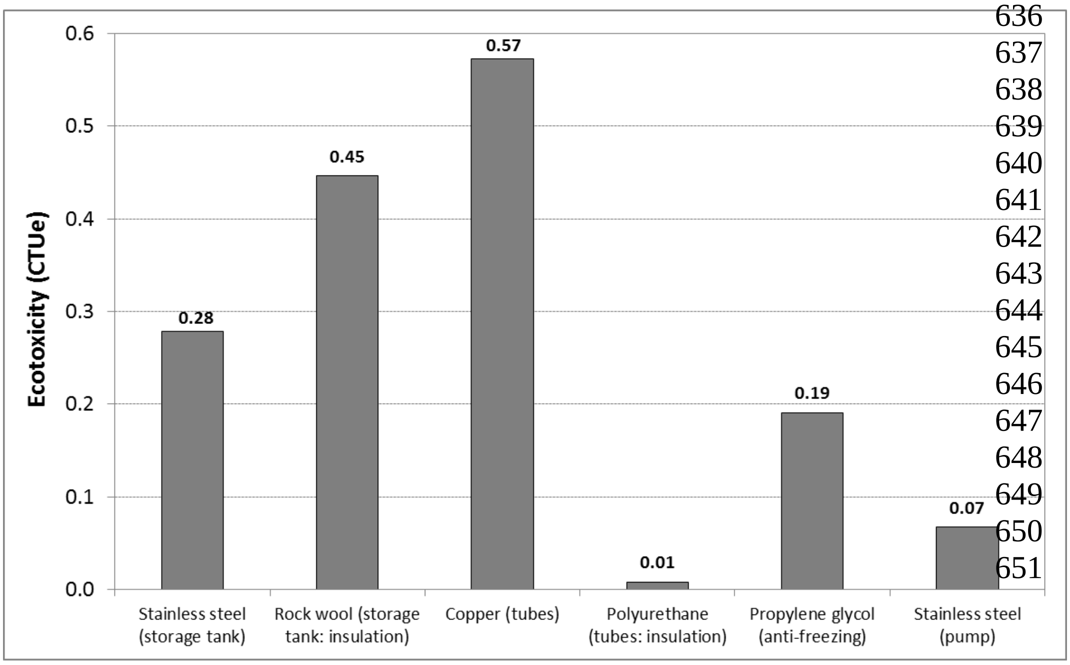


Figure 10. USEtox. Material manufacturing of the supplementary elements of the system in terms of: a) Human toxicity (cancer and non-cancer), b) Ecotoxicity. Scenario «without recycling».

3.7. Comparisons with the literature

In Table 8 the findings of the present study are compared with the literature and it can be noted that, in some cases, there is quite good agreement. For example, in the report IEA (2010) a global energy requirement of 1.71 GJ and a GWP of 101.2 kg

$CO_{2.eq}$ (functional unit: 1 m^2 of evacuated-tube collector) were found. The present system, based on EE and EC, by taking into account only the impact of the manufacturing of the vacuum-tube collectors, shows: i) 2.44 (without recycling) and 0.46 (with recycling) GJ_{prim} per m^2 of absorber, ii) 146.98 (without recycling) and 22.45 (with recycling) kg $CO_{2.eq}$ per m^2 of absorber. The cases with recycling mentioned above include the following materials: glass, aluminium, copper (Lamnatou et al., 2016). Regarding GPBTs of evacuated-tube collectors, one of the cases studied by Hang et al. (2012) presented a value of around 0.1 years. The present system shows GPBTs (equation based on material manufacturing of the vacuum-tube collectors) 0.5 years for the scenario «without recycling» and 0.1 years for the scenario «with recycling» (Lamnatou et al., 2016).

Regarding ReCiPe PBT, in the literature there is a study about a BI concentrating PV configuration for different cities (Barcelona, Seville, London, Aberdeen, Marseille, Paris) and electricity mixes (Lamnatou et al., 2017). In the case of the system mentioned above, the studied French cities (scenario: without material replacement) presented the following ReCiPe PBTs: 29.58 years the city of Paris and 16.52 years the city of Marseille. For the other studied cities (Spain: Barcelona, Seville; UK: London, Aberdeen) and for the scenario «without material replacement», ReCiPe PBTs ranged from 3.76 to 4.53 years (Lamnatou et al., 2017). This reference has been cited since in the literature there are no studies about ReCiPe PBT of solar thermal collectors which include comparisons between French and Spanish cities/electricity mixes. Certainly, the two systems (system of the present article vs. system investigated by Lamnatou et al. (2017)) have different functionalities: The system of the present work produces thermal energy based on vacuum-tube solar thermal collectors whereas the system that has been evaluated by Lamnatou et al. (2017) produces electricity based on concentrating PVs. Therefore, a direct comparison between these two systems is not possible. Nevertheless, in both cases ReCiPe PBTs show similar tendencies, i.e. high values for the studied French cities and considerably lower values for the studied Spanish cities. Related to the findings mentioned above, in the article by Lamnatou et al. (2017) there is a discussion: The high ReCiPe PBTs of the studied French cities are related to the low avoided ReCiPe impact ($I_{out.a}$: Equation 1) due to the distinctive features of the French electricity mix (high penetration of nuclear energy, low CO_2 emissions, etc.: Source: Réseau de Transport d'Électricité (RTE), France, 2017).

In addition, based on the investigation by Lamnatou et al. (2018b) about BIST LCA according to ReCiPe endpoint approach/single-score, the life-cycle impacts were calculated to be 0.017 and 0.014 Pts per kWh of thermal energy produced, in the case «without recycling» and «with recycling», respectively. The values mentioned above are for the following case: flat-plate gutter-integrated collectors, including aluminium gutter, option without PCM. In the present work (Table 8) this impact ranges from 0.009 to 0.012 Pts per kWh of thermal energy produced, depending on the scenario. It should be highlighted that the present solar thermal system is based on vacuum-tube technology whereas the solar thermal system that has been investigated by Lamnatou et al. (2018b) consists of flat-plate collectors.

From Table 8 it can be noted that, in the literature, some studies compare flat-plate with evacuated-tube solar thermal collectors. One of these works is that presented by Hoffmann et al. (2014). It was noted that, from an environmental perspective, the evacuated-tube collectors are the best choice.

Table 8. Comparisons between the present results and the literature (mainly in terms of evacuated-tube solar thermal collectors).

Study	**Type of system**	**Environmental issues/methods**	**Results with emphasis on evacuated-tube collectors**
Present work	16 solar thermal collectors based on vacuum-tube technology	ReCiPe midpoint/ endpoint; USEtox	**ReCiPe PBTs (without inputs for pumping/auxiliary heating; Reference: 30-year lifespan):** 18.14 years (France´s electricity mix; WITHOUT recycling) 15.48 years (France´s electricity mix; WITH recycling) 4.03 years (theoretical scenario: Spain´s electricity mix; WITHOUT recycling) 3.44 years (theoretical scenario: Spain´s electricity mix; WITH recycling) **ReCiPe endpoint single-score:** 0.010 and 0.012 Pts/kWh for 30-year and 20-year lifespan, respectively (WITHOUT recycling) 0.009 and 0.011 Pts/kWh for 30-year and 20-year lifespan, respectively (WITH recycling)
Lamnatou et al. (2016)	The system of the present work (vacuum-tube collectors) vs. a similar system with flat-plate collectors	EE; EC; EPBT; Energy return on investment; GPBT	Results for the vacuum-tube system: **EPBTs:** 0.5 years (WITHOUT recycling), 0.1 years (WITH recycling) **GPBTs (equation based on material manufacturing of the collectors):** 0.5 years (WITHOUT recycling), 0.1 years (WITH recycling) **EE:** 2.44 GJ_{prim}/m^2 (WITHOUT recycling), 0.46 GJ_{prim}/m^2 (WITH recycling) **EC:** 146.98 kg $CO_{2.eq}/m^2$ (WITHOUT recycling), 22.45 kg $CO_{2.eq}/m^2$ (WITH recycling) Approximately 0.01 kg $CO_{2.eq}$/kWh (20-year output; EC only for material manufacturing of the collectors; WITHOUT recycling)
Carlsson et al. (2014)	Evacuated-tube, flat-plate and polymeric collectors	EI99; IPCC GWP 100a; CED	**EPBTs (system with an evacuated-tube collector of 8.2 m^2):** 1.7 years (based mainly on primary metals), 1.3 years (based on secondary metals) With respect to climatic and environmental performances, evaluated by means of LCA, the polymeric solar system was found to be the best option
Greening and Azapagic (2014)	Evacuated-tube vs. flat-plate collectors	CML 2 Baseline 2001	**EC:** Evacuated-tube system: 0.039 kg $CO_{2.eq}$/kWh (regions with low solar irradiation)
Hang et al. (2012)	Evacuated-tube vs. flat-plate collectors	CED; EPBT; IPCC GWP 100a; GPBT	**GPBTs (different scenarios for evacuated-tube collectors were examined):** A certain case showed a value of 0.1 years
Hernandez and Kenny (2012)	Evacuated-tube vs. flat-plate collectors	EE; EPBT; Net energy ratio	**EPBT (scenario: Lavagh, Co Sligo):** 1.2 years (based on predicted savings)
Report IEA (2010)	Evacuated-tube collector	Global energy requirement; GWP	**Global energy requirement:** 1.71 GJ **GWP:** 101.2 kg $CO_{2.eq}$ Functional unit: 1 m^2 of evacuated-tube collector

4. BUILDING-INTEGRATED SOLAR SYSTEMS: ENVIRONMENTAL ISSUES

Based on the findings of the present study as well as based on the literature, in the present section critical parameters that influence the environmental profile of BI solar systems are presented and discussed.

Some materials that are related to a façade, a wall, etc., and are part of a BI solar system can considerably affect the environmental performance of the whole BI solar installation. For instance, the BIST system that has been studied in the present article includes the gutter, a component that could also be considered as element of the building, and not as part of the solar system. In the frame of the present LCA study, the gutter has been included in order to provide a complete picture about the environmental performance of the proposed BIST system since the basic material of the gutter is aluminium, i.e. an energy-intensive material with high environmental impact (primary aluminium) (Sources: SimaPro; ecoinvent).

Towards the development of sustainable products, there are studies that propose the adoption of alternative materials for solar thermal collectors, e.g. polymeric materials (Carlsson et al., 2014).

Some additional parameters that influence the output of a BI solar system, and therefore its environmental profile, are the following: working fluid, passive vs. active configurations, shadow effect, systems with sunlight concentration vs. systems without sunlight concentration, opaque vs. transparent (and semi-transparent) configurations, type of application, end-of-life and disposal, tilt angles – orientations – latitude, type of integration into the building, durability and lifespan of the adopted materials (Lamnatou and Chemisana, 2017) and, for some environmental indicators, the electricity mix of a country (Lamnatou et al., 2017).

In some cases, the materials of the storage system present a considerable environmental impact. For instance, there are studies which propose the combination of BI solar systems with PCM components. In the literature, LCA studies about BIST systems with fatty-acid PCM heat storage/insulation have been presented (Lamnatou et al. 2018a, 2018b). It was found that PCM environmental profile depends on the environmental indicator. Based on USEtox human toxicity/cancer, USEtox ecotoxicity and ReCiPe endpoint with characterisation (species.yr), it was verified that the PCM component (fatty acid) presents an impact considerably higher in comparison to the other parts of the BIST system (Lamnatou et al., 2018b). Moreover, in the case of PV systems, the storage may include batteries that influence the environmental profile of the whole system (Üçtuğ and Azapagic, 2018b).

Another issue is related to the weight of the BI solar collectors/panels. There are studies that propose the adoption of alternative, lightweight materials in order to reduce the total weight of the system (Martins et al., 2018).

In the case of BI solar systems which include PV cells, the type of the PV-cell material can remarkably influence the environmental profile of the whole system (Lamnatou and Chemisana, 2017).

Certainly, the adoption of recycling, e.g. in the case of systems with large amounts of metals, offers considerable reduction in the environmental impact and more efficient utilisation of resources than using primary materials. In subsection 3.1.3, the role of recycling has been discussed.

In light of the references and the discussion presented above, in Table 9 a classification of some parameters is presented.

Table 9. Factors which influence the environmental profile of a BI solar system.

Type of BI solar system	Factor	Brief discussion
Solar thermal, PV or Photovoltaic/Thermal (PVT)	The materials of the façade, wall, etc. that are part of the whole BI solar system	For instance, the gutter of the BI system of the present study considerably influences the impact of the whole system since aluminium is its basic component
Solar thermal or PVT	Working fluid (e.g. water vs. air)	Due to the lower thermal efficiency of the air heat extraction, the environmental profile of water-based systems is expected to be better than that of the air-based ones
Solar thermal or PVT	Passive vs. active configurations (in terms of the flow of the working fluid)	In general, an active configuration is more complicated because additional materials/inputs such as fan and electricity to run the fan, are needed
Solar thermal, PV or PVT	Shadow effect – tilt angles – orientation – latitude	All these factors influence the output of the system
Solar thermal, PV or PVT	Concentrating vs. non-concentrating systems	In general, sunlight concentration offers higher energy output; in the case of PV or PVT systems, it also means replacement of the energy-intensive PV-cell material with a concentrator
Solar thermal, PV or PVT	Opaque vs. transparent (or semi-transparent) configurations	Transparency influences the amount of sunlight that enters into the building
Solar thermal, PV or PVT	Type of application and type of building integration	For instance, applications in the frame of buildings (façade, wall, etc.) and greenhouses
Solar thermal, PV or PVT	Weight of the materials, type of the materials of the storage system, end-of-life and disposal, type of the PV cells (for PV and PVT systems), lifespan of the materials, adoption of alternative materials (e.g. polymeric)	For example, the materials of the storage system, in some cases (e.g. batteries and PCM), can considerably influence the environmental profile of the whole system
Solar thermal, PV or PVT	Electricity mix of a country	Certain environmental indicators include calculations which are directly associated with the electricity mix of a country
Solar thermal, PV or PVT	Recycling	In many cases, these types of systems consist of large quantities of metals; by means of recycling of the metallic parts of a system, considerable impact reduction can be achieved

5. CONCLUSIONS

The present article is an LCA study about the environmental profile of a vacuum-tube BIST system, based on ReCiPe midpoint/endpoint and USEtox. It is highlighted under which conditions these types of systems offer eco-friendly solutions in the building sector. Moreover, critical parameters are discussed.

On the basis of ReCiPe midpoint and by taking into account material manufacturing of the 16 collectors and the additional elements of the system (scenario «without recycling»), among glass-, aluminium-, copper- and steel-based components, the copper-based ones present the highest impact in 15 of the 18 impact categories. More analytically, in the case of Freshwater eutrophication, copper has a score that is around 30 times higher comparing to that of aluminium. For Human toxicity, copper presents a value which is approximately 56 times higher than that of aluminium. For the category of Freshwater ecotoxicity, the score of copper is about 40 times higher in comparison to that of aluminium. In the case of Marine ecotoxicity, copper shows a value which is approximately 37 times higher comparing to that of aluminium. In addition, for Metal depletion, copper presents a score that is around 537 times higher than that of aluminium.

In terms of the life-cycle results, ReCiPe PBT shows a value of 18.14 years in the case of France´s electricity mix and for the scenario «without recycling». According to a hypothetical scenario, the adoption of Spain´s electricity mix, due to the remarkable differences with the electricity mix of France, presents a ReCiPe PBT of 4.03 years (scenario «without recycling»).

By means of recycling of glass, metals and plastics (for the other materials, landfill has been assumed) ReCiPe PBT is reduced: 1) from 18.14 to 15.48 years based on French electricity mix, 2) from 4.03 to 3.44 years based on Spanish electricity mix. Consequently, these findings reveal that recycling offers a remarkable reduction in ReCiPe PBT.

The results according to USEtox by considering all the components of the 16 collectors and the supplementary elements of the system for material manufacturing and for the scenario «without recycling», demonstrate that the material with the highest total score with respect to: 1) human toxicity/cancer and ecotoxicity is copper, 2) human toxicity/non-cancer is propylene glycol. The USEtox findings verify that the adoption of recycling of the metals offers a considerable reduction in the impact: 20-95%, depending on the type of the metal and the impact category.

A critical discussion about factors that influence the environmental profile of BI solar systems shows that these parameters include multiple aspects such as the materials of the storage system, the type of building integration, the use of alternative materials with low environmental impact and the waste-management options.

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REFERENCES

Akyüz, M.K., Altuntaş, Ö., Söğüt, M.Z., 2017. Economic and Environmental Optimization of an Airport Terminal Building’s Wall and Roof Insulation. Sustainability 2017, 9, 1849; doi:10.3390/su9101849

Arnaoutakis, N., Souliotis, M., Papaefthimiou, S., 2017. Comparative experimental Life Cycle Assessment of two commercial solar thermal devices for domestic applications. Renew. Energy 111, 187-200.

Carlsson, B., Persson, H., Meir, M., Rekstad, J., 2014. A total cost perspective on use of polymeric materials in solar collectors - Importance of environmental performance on suitability. Appl. Energy 125, 10-20.

Comodi, G., Bevilacqua, M., Caresana, F., Pelagalli, L., Venella, P., Paciarotti, C., 2014. LCA analysis of renewable domestic hot water systems with unglazed and glazed solar thermal panels. Energy Procedia 61, 234-237.

Cristofari, C., 2006. Device for collecting rainwater and solar energy originating from light radiation. Patent no. WO 2006/100395 A1: 28/09/2006.

Echarri-Iribarren, V., Rizo-Maestre, C., Echarri-Iribarren, F., 2018. Healthy Climate and Energy Savings: Using Thermal Ceramic Panels and Solar Thermal Panels in Mediterranean Housing Blocks, Energies 11, 2707; doi:10.3390/en11102707.

ecoinvent, http://www.ecoinvent.org/database/database.html

El Sistema Eléctrico Español, AVANCE, 2017, RED Eléctrica de España, Report.

Greening, B., Azapagic, A., 2014. Domestic solar thermal water heating: a sustainable option for the UK? Renew. Energy 63, 23-36.

Hang, Y., Qu, M., Zhao, F., 2012. Economic and environmental life cycle analysis of solar hot water systems in the United States. Energy Build. 45, 181-188.

Hernandez, P., Kenny, P., 2012. Net energy analysis of domestic solar water heating installations in operation. Renew. Sustain. Energy Rev. 16, 170-177.

Hoffmann, R., Brondani, M., Pappis, F., Friderichs, A., Serafini, S., Foletto, E.L., 2014. Economic-environmental comparison between flat plate and evacuated tube solar collectors. Global NEST J 16(6), 1100-1110.

ISO 14040:2006. Environmental management - Life cycle assessment - Principles and framework.

ISO 14044:2006. Environmental management - Life cycle assessment - Requirements and guidelines.

Jungbluth, N., 2005. Life Cycle Assessment of Crystalline Photovoltaics in the Swiss ecoinvent Database. Prog. Photovolt: Res. Appl. 13, 429–446.

Kalogirou, S., 2009. Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters. Solar Energy 83, 39-48.

Kylili, A., Fokaides, P.A., Ioannides, A., Kalogirou, S., 2018. Environmental assessment of solar thermal systems for the industrial sector. J. Clean. Prod. 176, 99-109.

Lamnatou, Chr., Baig, H., Chemisana, D., Mallick, T.K., 2017. Dielectric-based 3D building-integrated concentrating photovoltaic modules: An environmental life-cycle assessment. Energy Build. 138, 514-525.

Lamnatou, Chr., Chemisana, D., 2017. Photovoltaic/thermal (PVT) systems: A review with emphasis on environmental issues. Renew. Energy 105, 270-287.

Lamnatou, Chr., Cristofari, C., Chemisana, D., Canaletti, J.L., 2016. Building-integrated solar thermal systems based on vacuum-tube technology: Critical factors focusing on life-cycle environmental profile. Renew. Sustain. Energy Rev. 65, 1199-1215.

Lamnatou, Chr., Motte, F., Notton, G., Chemisana, D., Cristofari, C., 2018a. Cumulative energy demand and global warming potential of a building-integrated solar thermal system with/without phase change material. J. Environ. Manage. 212, 301-310.

Lamnatou, Chr., Motte, F., Notton, G., Chemisana, D., Cristofari, C., 2018b. Building-integrated solar thermal system with/without phase change material: Life cycle assessment based on ReCiPe, USEtox and Ecological footprint. J. Clean. Prod. 193, 672-683.

Lamnatou, Chr., Notton, G., Chemisana, D., Cristofari, C., 2014. Life cycle analysis of a building-integrated solar thermal collector, based on embodied energy and embodied carbon methodologies. Energy Build. 84, 378-387.

Lamnatou, Chr., Chemisana, D., Mateus, R., Almeida, M.G., Silva S.M., 2015a. Review and perspectives on Life Cycle Analysis of solar technologies with emphasis on building-integrated solar thermal systems. Renew. Energy 75, 833-846.

Lamnatou, Chr., Notton, G., Chemisana, D., Cristofari, C., 2015b. The environmental performance of a building-integrated solar thermal collector, based on multiple approaches and life-cycle impact assessment methodologies. Build. Environ. 87, 45-58.

Lenz, K., Wittstock, B., Jäger, M., Schneider, S., Sedlbauer, K., 2012. LCA of energy generating components for facade integration in existing high-rise buildings. Int. J. Sustain. Build. Tech. Urban Develop. 3(3), 168-176.

Martins, A.C., Chapuis, V., Sculati-Meillaud, F., Virtuani, A., Ballif, C., 2018. Light and durable: Composite structures for building-integrated photovoltaic modules. Prog. Photovolt. Res. Appl. 26, 718–729.

Meneghelli, A., 2018. Whole-building embodied carbon of a North American LEED-certified library: Sensitivity analysis of the environmental impact of buildings materials. Build. Environ. 134, 230-241.

Michael, J.J., Selvarasan, I., 2017. Economic analysis and environmental impact of flat plate roof mounted solar energy systems. Solar Energy 142, 159-170.

Otanicar, T.P., Golden, J.S., 2009. Comparative Environmental and Economic Analysis of Conventional and Nanofluid Solar Hot Water Technologies. Environ. Sci. Tech. 43, 6082-6087.

Palacios-Jaimes, G.Y., Martín-Ramos, P., Rey-Martínez, F.J., Fernández-Coppel, I.A., 2017. Transformation of a University Lecture Hall in Valladolid (Spain) into a NZEB: LCA of a BIPV System Integrated in Its Façade. Hindawi International Journal of Photoenergy, Volume 2017, Article ID 2478761, 11 pages, https://doi.org/10.1155/2017/2478761

PRé, various authors, SimaPro Database Manual, Methods Library, Report version 2.6, May 2014.

Report IEA (2010). Solar Heating and Cooling Programme, International Energy Agency, Task 38, Solar air-conditioning and refrigeration, life cycle assessment of solar cooling systems, a technical report of subtask D, Subtask Activity D3, Date: December 2010. Beccali, M.: Editor. Contributions from Beccali, M., Cellura, M., Ardente, F., Longo, S., Nocke, B., Finocchiaro, P., Kleijer, A., Hildbrand, C., Bony, J., Citherlet, S.

Report NEEDS (2007). Final report on technical data, costs and life cycle inventories of nuclear power plants, Project no: 502687, NEEDS, New Energy Externalities Developments for Sustainability, Sixth framework programme, Authors: Lecointe, C., Lecarpentier, D., Maupu, V., Le Boulch, D., Richard, R. – EDF R&D, With contributions from: Garzenne, C. - EDF R&D, Bachmann, T. M., EIFER and a literature survey on costs and provision of LCI data by: Dones, R. – PSI.

Réseau de Transport d'Électricité (RTE), France (2017), http://bilan-electrique-2017.rte-france.com/production/le-parc-de-production-national/#

Rosenbaum, R.K., Huijbregts, M.A.J., Henderson, A.D., Margni, M., McKone, T.E., van de Meent, D., et al., 2011. USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties. Int. J. Life Cycle Assess. 16, 710–727.

Samuelsson, C., Björkman, B., 2014. Chapter 7 – Copper Recycling. Handbook of Recycling. State-of-the-art for Practitioners, Analysts, and Scientists. 2014, Pages 85–94.

SimaPro, https://simapro.com/

Smarter HOUSE, https://smarterhouse.org/water-heating/replacing-your-water-heater

Soo, V.K., Peeters, J., Paraskevas, D., Compston, P., Doolan, M., Duflou, J.R., 2018. Sustainable aluminium recycling of end-of-life products: A joining techniques perspective. J. Clean. Prod. 178, 119-132.

Uctug, F.G., Azapagic, A., 2018a. Life cycle environmental impacts of domestic solar water heaters in Turkey: The effect of different climatic regions. Sci. Tot. Environ. 622-623, 1202-1216.

Üçtuğ, F.G., Azapagic, A., 2018b. Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries. Sci. Tot. Environ. 643, 1579–1589.

Zabalza, I., Scarpellini, S., Aranda, A., Llera, E., Jáñez, A., 2013. Use of LCA as a Tool for Building Ecodesign. A Case Study of a Low Energy Building in Spain. Energies 6, 3901-3921; doi:10.3390/en6083901